Finding Galaxy Clusters and Groups in Chandra Archival Images

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ABSTRACT

We present preliminary results from a multiwavelength search for galaxy groups and clusters imaged in X-rays by Chandra and in the optical by the Chandra Multiwavelength Project (ChaMP). The ChaMP's X-ray pipeline includes automatic extended source detection, which is augmented and verified by visual inspection. We extend the detection and verification of these galaxy associations to the optical via (1) Voronoi Tesselation and Percolation analysis of galaxy clustering and (2) early-type galaxy red sequences in color-magnitude diagrams constructed from 3-filter deep optical images obtained with the MOSAIC CCD at NOAO 4-meter telescopes. The deep sensitivity of our imaging, combined with the multiwavelength approach, offers a diverse cluster sample probing both high redshifts and low luminosities. We highlight several new clusters detected by the ChaMP.

WHY CLUSTERS?

- Clusters are the largest virialized (gravity-dominated) objects in the Universe, corresponding to high peaks in the initial density field.
- Growth of mass fluctuations on cluster scales is strongly dependent on the total mass content of the Universe (the density parameter Ω), so evolution of the cluster mass function provides a sensitive cosmological test.
- Recent work suggests strong evolution of the baryon mass function between $z > 0.4$ and the present (Vikhlinin et al. 2003).
- Observed $M_{gas} - T - L_X$ correlations show that high-z clusters were denser; hotter and more luminous for a given mass.
- While this is expected in hierarchical self-similar formation theories, the details of the observed evolution contradict the self-similar predictions (Vikhlinin et al. 2002).

WHY X-RAYS?

- X-ray selection is less prone to projection effects.
- X-ray parameters L_X and T_X are closely related to cluster mass – and the ICM comprises $\sim 15\%$ of the total cluster mass.

All-sky surveys, such as ROSAT All-Sky Survey (Collins et al. 2000; Ebeling et al. 2000; Bhringer et al. 2000) and Extended Medium-Sensitivity Survey (Gioia & Luppino 1994), as well as pointed ROSAT observations (Scharf et al. 1997; Romer et al. 2000), have been used to produce cluster catalogs at X-ray wavelengths.

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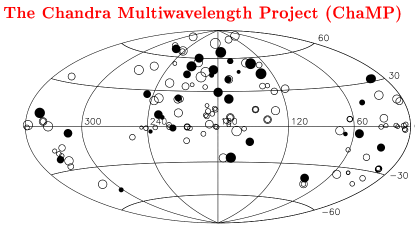
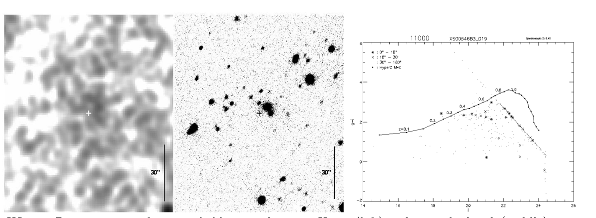
The Chandra Multiwavelength Project (ChaMP)



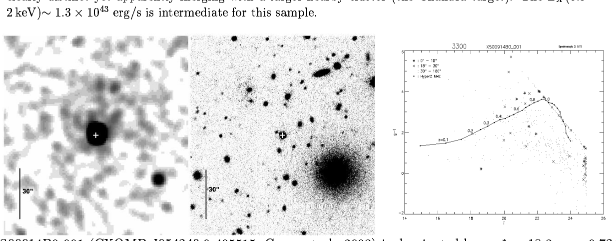
The ChaMP is a serendipitous X-ray source survey emphasizing deep, wide-field followup optical imaging (NOAO 4m/Mosaic) in g', r', and i' SDSS filters and multi-object spectroscopy from NOAO, MMT, and Magellan. The ChaMP includes $|b| > 20$ archival AO1 + AO2 Chandra fields, excluding ACIS subarrays, PI deep fields, and bright extended sources (yields ~ 137, or $\sim 20\%$ of AO1 + AO2 Chandra fields). Filled circles are ACIS-I, open are ACIS-S pointings.

OPTICAL PROPERTIES of X-RAY CLUSTERS

- 15 sources were detected and flagged as extended by XPIPE.
- 6 additional sources were manually flagged as extended during the Chandra visualization and verification (V&V) process.
- 4 were rejected as spurious (low counts), 2 were parts of larger extended target clusters, 3 were associated with an interacting galaxy system, and 4 had no deep optical imaging.
- 8 X-ray selected clusters remain, from which we present 4 examples here.



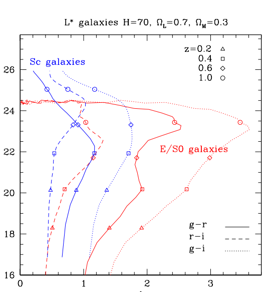
XS00546B3_019 is one of two probable new clusters. X-ray (left) and optical i-band (middle) images are shown, along with color-magnitude data (right). This $z = 0.41$ cluster is a relatively small system, clearly distinct yet apparently merging with a larger nearby cluster (the Chandra target). The L_X(0.5-2 keV)$\sim 1.3 \times 10^{43}$ erg/s is intermediate for this sample.



XS00914B0_001 (CXOMP J054240.9-405515; Green et al. 2003) is dominated by a $r^* = 18.3$, $z = 0.724$ quasar in the X-ray image (left), but is surrounded by a halo of weak extended emission. As with the other high-z clusters in this sample there is no clear red sequence observed for this cluster, although L_* ellipticals at this redshift should be easily detectable at $r^* \sim 23$.

OPTICAL CLUSTER COLORS

- Our SExtractor photometry (Bertin & Arnouts 1996) yields g', r', and i' mags for ChaMP fields from deep NOAO/Mosaic imaging (Green et al. 2003).
- For sources within 0-18 arcsec, 18-30 arcsec, 30-180 arcsec of the X-ray centroid we constructed $(g'-i')$ vs. i' color-magnitude diagrams, to check for the existence of a cluster *red sequence* caused by a population of early-type galaxies usually present in galaxy clusters (Gladders & Yee 2000). Red sequence colors can also be used for phtometric redshifts by comparison to the expected theoretical colors (we use the *HyperZ* code of Bolzonella et al. 2000).

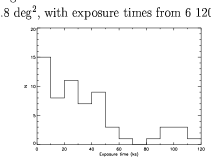


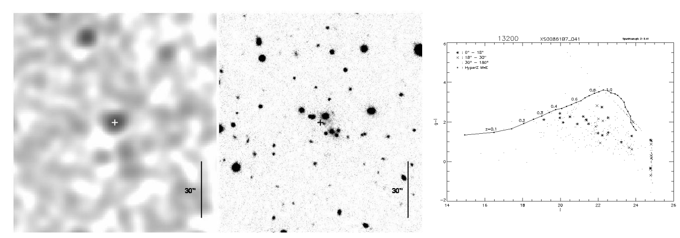
Theoretical color vs. r-magnitude curves for a typical cluster elliptical galaxy at a range of redshifts (from 0.05 to 1.50), in three color bands.

- For several clusters, we compare these photo-zs to spectroscopic redshifts obtained by the ChaMP for a single object closest to the X-ray centroid.

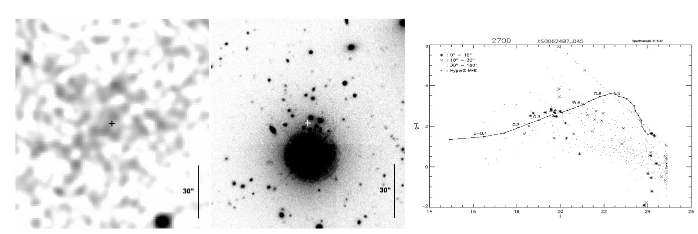
ChaMP XPIPE

- X-ray data were reduced via the automatic pipeline XPIPE to remove hot pixels, cosmic rays, and other artifacts (Kim et al. 2003).
- The wavelet transform source detection algorithm `wavdetect` (Freeman et al. 2002) was applied to obtain an index of source positions and properties for further inspection.
- A prototype extended source detection algorithm fits each detected source with a circular Gaussian profile in the S band (0.3 - 2.5 keV), and compares the fitted σ parameter with the σ of the Chandra PSF for the off-axis angle of the source. An extended source must have $\sigma > 1.5 \times 40\%$ encircled energy radius.
- A total of 62 pointings from the ChaMP database were scanned for extended sources, covering a total of 5.8 deg^2, with exposure times from 6 120 ksec, with a mean of 36 ksec.





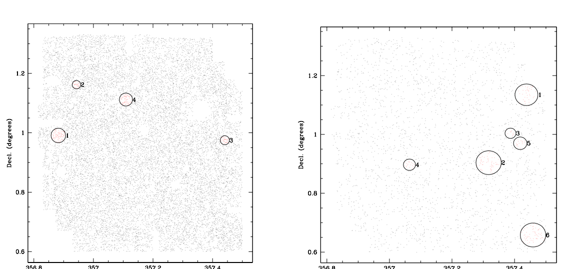
XS00861B7_041 (CXOMP J23415.7+005353 in Green et al. 2003) has weak, only marginally extended X-ray emission (left), but a dense core of early-type galaxies in optical (middle) at the same location with a clear red sequence (right) indicates that this is either a group, or an AGN in a cluster. We tentatively assign a redshift of $z = 0.41$ to the cluster, based on a spectrum (Magellan 6.5m with LDSS2 03 Dec 2002) of the brightest $r^* = 19.7$ galaxy. The source flux of $f_X = 10^{-15}$ erg cm^{-2} s^{-1} at this redshift corresponds to log $L_X = 41.84$.



XS00624B7_045 is one of three ChaMP-published clusters to date (CXOMP J033912.2-352614; Green et al. 2003). Cluster signatures are evident in red sequence photometry (above, although it is slightly bluer than expected), X-ray imaging (left) and optical imaging (middle, close to a bright $V = 12$ foreground star.) Fixing to an average cluster β-model profile $\beta = 0.6$, we derive a core-radius $r_c = 47 \pm 12$ arcsec. The cluster is only detectable to about $3r_c$, within which there are 1630 counts. The (0.5-2 keV) flux is therefore 3×10^{-13} erg cm^{-2} s^{-1}. If $z \sim 0.4$, then L_X(0.5-2 keV)$\sim 1.3 \times 10^{43}$erg/s.

X-RAY PROPERTIES of OPTICAL CLUSTERS

- X-ray upper limits and stacking of optically-detected clusters can newly probe the very low L_X cluster regime. *Are some clusters gas-poor?*
- Optical galaxy positions are input as the seeds for the **Voronoi Tessellation and Percolation (VTP)**, and the Voronoi cell around each galaxy is interpreted as the effective area that each galaxy occupies in space. Taking the inverse of these areas gives a local density at each galaxy in two dimensions. This information is then used to threshold and select galaxy members that live in highly overdense regions, which we identify as clusters (e.g., Ramella 2002).
- Color-filters lower the background, decrease projection effects, and increase the number of detections.
- VTP overdensity detections can be verified via cluster red sequences and/or lower significance X-ray enhancements.



Comparison between unfiltered (left) and filtered ($1.8 < (g-i) < 2.7$; right) VTP runs on the NOAO/Mosaic optical photometric data for obsid 861. Sources are marked in green. The ChaMP cluster is located as the only source in the left half of the filtered diagram. The CMD generated using the VTP centroid shows the red sequence seen at $(g-i)$=2, and verifies the optical cluster detection independent of the X-ray detection in obsid 861 above.

SUMMARY

- The ChaMP project identifies new X-ray emitting clusters in sensitive X-ray and optical multicolor imaging.
- In 6 pilot fields, we identified 8 clusters, most at $z > 0.4$, several of which are shown here.
- We find several X-ray clusters with bright point-source AGN, which in some cases masks detection of the extended emission. We are enhancing the ChaMP XPIPE cluster detection algorithm to remove detected point sources and search for extended emission.
- Voronoi Tesselation with color filtering - verified by red sequences in color-magnitude diagrams - finds optical clusters with sensitive X-ray data in our ChaMP fields.
- Though our photometry matches SDSS field galaxies in the color-redshift plane, cluster red sequences appear to be bluer than predicted. This discrepancy is under investigation.

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